Pyramid-shaped pixels for full-color organic emissive displays

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Organic electroluminescent emissive displays are composed by pixels consisting red-green-blue (RGB) light-emitting diodes (LEDs) in a planar arrangement. When operated, these RGB LEDs are biased independently to produce the required color. In this manuscript, we describe a promising pixel structure, the pyramid-shaped pixel (PSP) for the integration of organic light-emitting diodes (OLEDs) in full-color organic emissive displays. The RGB light-emitting diodes are constructed on the walls of the pyramid structure. When operated, the RGB LEDs emit photons through the base of the pyramid structure, hence these RGB LEDs share the same emissive area to produce the required color. The PSP structure offers the advantage of being a full color emissive pixel comprising of individual RGB OLEDs with very high resolution. In addition, pyramid pixel does not require shadow mask to pattern the organic materials during the vacuum deposition process.

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Organic light-emitting diodes (OLEDs) are promising candidates for the next generation full-color, flat panel displays. The advantages of OLED-based displays include full-color emissions, low power consumption, low cost of fabrication, high contrast, and potentially high lateral resolution. Although OLEDs of various emission colors show good device performances and long lifetimes, the patterning of these electroluminescent organics, particularly for large area panels continues to be a challenge. Several approaches have been demonstrated (Refs. 2–6). However, none of them can fully utilize the above-mentioned advantages of these materials. The characteristic low weight and thin film structure of the organic emissive displays make them likely candidates for information displays in portable electronic devices such as cellular phones where power efficiency has become an important issue. In order to achieve the optimum performance from full-color organic emissive displays, it is preferable to construct pixels of individual red, green, and blue OLEDs. These pixels are currently being fabricated through traditional methods such as shadow masking, which limits the resolution and panel size of the resultant displays. The best reported organic full-color emissive display has only a quarter video graphic adaptor (VGA, 640 × 480) resolution. On the other hand, in the pyramid-shaped pixel (PSP) structure, the individual red green blue (RGB) OLEDs comprising the pixel share the same emission area on the substrate. This leads to an enhancement of the lateral resolution of the organic emissive display by a factor of 3 to 4. In addition, since this is a mask-free fabrication process, the resolution and panel size of the display will not be limited by constraints imposed by the shadow mask technique.

The structures of several different forms of the PSPs are shown in Fig. 1. The number of available surfaces per pixel distinguishes these structures. Figure 1(a) shows a PSP with three available surfaces, which is ideal for the deposition of RGB OLEDs. Figure 1(b) shows a truncated PSP with four available surfaces, which is ideal for the deposition of OLEDs with three or four different emission colors. Alternatively, ridge-shaped pixels with two available surfaces (not shown in Fig. 1) can be used to fabricate multicolor organic emissive devices, if full color is not required.

The fabrication of the OLED-based PSP is fairly simple. The substrate with PSPs on the surface can be fabricated through a standard plastic molding process. Each pixel provides several flat surfaces for the deposition of OLEDs with different emission colors. Since the vapor phase deposition of the organic materials is typically a line-of-sight technique, the substrates can be tilted in such a way that only one of the flat surfaces of the PSP faces the vapor flux at any time. Since the other surfaces are oriented at rather large angles from each other (defined by the normals to their surfaces), a shielding effect is achieved for these surfaces. Therefore, PSPs are able to achieve the patterning of individual RGB OLEDs without the use of external shadow masks. More importantly, the pixel size is significantly reduced since the light-emitting area is shared by the OLEDs in the PSP structure. This technology can potentially offer a much higher lateral resolution. The advantages of OLED-based PSPs are listed below.

1. The fabrication process is mask-free, thereby reducing the processing steps and ultimately the cost of fabrication.
2. A high display resolution for the organic emissive panels made of PSPs.
3. Flexibility in the choice of the substrate, since molded plastic sheets, silicon wafers, glass, or a combination of the above can be used.
4. Significant amount of the emission light is trapped within the substrate due to the wave guiding effect. This problem would be alleviated for the PSP, since the substrate no longer presents planar surfaces. It is therefore anticipated that the quantum efficiency of OLEDs on PSP will be enhanced.
5. Due to the multiple folding surfaces on the substrate, this pyramid structure also provides an ideal approach for the fabrication of high brightness organic lamps.

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A full-color, organic light-emitting panel can be realized when RGB OLEDs are fabricated on the different surfaces of each pixel. The deposition of the RGB OLEDs can be carried out sequentially for each surface using a specific emissive material or simultaneously if the direction of each organic vapor can be controlled precisely. The substrate is tilted at such an angle that the deposition of the organic compound occurs only at the surface facing the vapor source while the other surfaces are masked from the vapor flux. To further enhance the shielding (or masking) effect, a dividing wall between each OLED can be introduced. This concept is schematically shown in Figs. 1a and 1b of Fig. 1.

In order to prove the principle and feasibility of deposition of organic thin films on the PSPs, we deposited an aluminum (III) tris(8-hydroxyquinolate) (Alq3) organic layer onto a commercially available plastic substrate with ridge-shape surface structure to mimic the pyramid structure.8 We could not find substrates with a PSP structure and hence used a substrate with a ridge-shaped structure formed on the surface to prove our point. Figure 2(a) shows the picture of the structure illuminated by an ultraviolet (UV) light source under a fluorescence optical microscope. The photoluminescence (PL) from the Alq3 was clearly observed from only one surface. Figure 2(b) shows the cross-section of the substrate. It is clear that the Alq3 is present only on one surface and not on both. The thickness of Alq3 thin film was only about 0.1 μm; too thin to be observed directly using a regular optical microscope. Hence, fluorescence optical microscopy becomes a handy technique to observe the Alq3 film.

One of the major challenges of the pyramid structure pixel is the electrical connection and the addressing of each RGB LEDs of the pixel. The addressing scheme for the pyramid pixel is the active matrix driving method controlled by thin film transistors (TFTs). TFT fabrication and the electrical connection from the TFT to each LED can be achieved by a two-step fabrication process. First step is the fabrication of TFTs on top of a transparent substrate, such as a glass plate. This fabrication process has been described elsewhere.9 After the completion of the TFTs and the necessary contact pads, the pyramid structures can be molded from plastics onto the proper positions on top of the glass substrate with openings for the electrical contact pads. Plastic molding is a simple and mature process, and it is anticipated that the TFTs and contact pads will be able to withstand the temperature during the plastic molding. Subsequently, the ITO transparent electrode can be sputtered on top of the pyramid structure. Due to the dividing walls between each surface of the pyramid structure (Fig. 1), it is anticipated that the electrical cross-talk between each LED can be avoided. For the fabrication of organic LEDs, a bi-layer structure consisting of a hole-transport layer and an electron-transport layer is required to achieve efficient devices. Usually, the electron transport layer (ETL) is also the light-emitting layer. A uniform deposition of the hole-transport layers over the entire substrate could be achieved by rotating the substrate inside the vacuum chamber. This can be followed by the sequential deposition of various ETLs or light-emitting layers onto specific surfaces of the PSP by the precise orientation of the substrates. Alternately, if the directionality of the vapor flux can be precisely controlled,
multiple depositions of the organic species can be carried out onto the different surfaces of the PSP structure in a single operation. After the deposition of organic layers, metal electrodes can be deposited on top of the organic layers, thereby completing the process of OLED fabrication.

Currently, the unique shape of the PSP makes the commercial procurement of these substrates difficult. Hence, to demonstrate our concept we used an optical prism (geometrically scaled-up version of the PSP structure) with three clear surfaces and two frosted end surfaces as the unit pixel to simulate the PSP. Red, green, and blue polymer lightemitting diodes (PLEDs) were glued to the three transparent surfaces with their light-emitting surfaces directed towards the prism. The PLEDs were fabricated in the structure: indium–tin–oxide (ITO)/PEDOT/polymer/calcium/aluminum. Poly(2-methoxy-5(2’-ethyl-hexoxy)-p-phenylene vinylene) (MEH-PPV), poly(phenylene vinylene) (PPV), and polyfluorene (PF) were used as the red, green, and blue emissive materials, respectively, for the PLEDs.

Figure 3 shows the pictures and EL emission spectra of the RGB PLEDs. The emission spectra were taken from the end surface of the prism. Each PLED emission from the prism is consistent with the individual emission spectrum taken from the device. This is an indication of minimal contribution from the EL-induced photoluminescence from other PLEDs, consistent with the observation from the stack OLEDs reported by the Princeton group.4 The corresponding Commission International de L’Eclairage (CIE) chart of the RGB PLEDs is also shown in Fig. 3. Within this chart, we have demonstrated the tuning of emissions between the green and blue LEDs. The coordinate of the CIE chart could be continuously adjusted by changing the bias between the blue and green LEDs. Figure 4 shows the picture of white light emission from the end surface of the prism. This white light is composed of contributions from the RGB PLEDs.

In summary, we have proposed and demonstrated a promising way of achieving a full color light-emitting pixel, the pyramid shape pixel (PSP), for the organic light-emitting panels, and displays. This is a shadow mask free fabrication process. The pyramid structure not only provides easy and low cost fabrication for the organic displays but also significantly enhances the resolution and panel size of the organic emissive display.

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8 3M Brightness Enhancement film BEF II 90/50, the period of the ridge is ~50 μm.