Revolutionary New Photolithography-Patterned AMOLED Display Bringing Technology Advances

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ABSTRACT

eLEAP is an OLED display that uses photolithography in its RGB sub-pixel patterning processes, developed by Japan Display Inc. (JDI). JDI is registering this trademark as "eLEAP". By adopting eLEAP into today's display products, various unparalleled values will be delivered. In this article, we will describe eLEAP's value propositions.

1 Background and Introduction

Since the beginning of evaporation RGB-OLED display's adoption in smartphone and smartwatch products, fine-metal-mask (FMM) has been dominantly used to separate adjacent sub-pixels [1]. Compared to white OLED technology, directly patterned RGB OLED displays tend to show better optical and electrical characteristics because, unlike white OLED displays, directly patterned RGB OLED displays do not require a color filter that absorbs a great portion of the outgoing light components [2]. However, using FMMs for OLED display mass production is not so easy. One of the biggest challenges is to secure the mask aperture positions right on the desired TFT substrate positions. In the case of a 326ppi display, one pixel size is 78um and the distance between adjacent sub-pixel to sub-pixel emission areas becomes 17~25um, which is considered a typical design due to today's FMM pixel position accuracy. It is not easy to shrink the distance, because FMM's aperture positions easily shift due to FMM related processes such as FMM stick tension welding, mask assembly, transportation, thermal expansion, gravity sagging, magnetic force, recurring mask cleaning, and so on. Controlling good aperture positions on mass-production-scale mother glasses need a lot of process know-hows. FMM will become the major challenge when higher aperture ratio or larger screen size designs are required.

Japan Display Inc. (JDI) has developed a new OLED display called eLEAP that does not require evaporation metal masks. JDI is registering the trademark "eLEAP" for displays made with lithography OLED patterning. eLEAP's sub-pixels are patterned by precision photolithography processes, which is why the sub-pixel to sub-pixel distance can be smaller than 16um, where FMMs cannot be typically mass producible. This precision sub-pixel patterning feature is one of eLEAP's uniqueness. In this paper, such eLEAP's advantages will be introduced.

2 Technical Advantages

2.1 Aperture Ratio

Fig. 1 shows the difference of sub-pixel to sub-pixel distance between a conventional FMM OLED display and eLEAP. When pixel aperture ratio is larger, one advantage is suppression of OLED device efficiency degradation, also known as lifetime. Because the emission area is larger, current density can be lowered for the intended luminance, which means current stress that applies to pixels can be weakened. The weakened current stress results in a longer lifetime. Another advantage is potential power reduction when the OLED device has a peak efficiency in roll-off curve at lower current density region. Larger aperture ratio allows a display to use current density regions with a higher luminescence efficiency.

(a) (b)

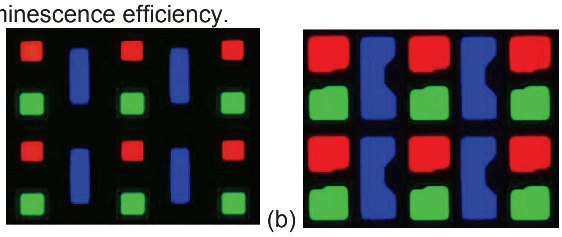

Fig. 1 (a) Pixels of FMM OLED (b) Pixels of eLEAP.

2.2 Vertical Structure

2.2.1 Common Layers

In terms of vertical OLED device stack-up, there is a difference between a conventional FMM OLED display and eLEAP. Evaporation OLED displays have many functional layers in the vertical stack-up. To manufacture RGB OLED displays on a mass production scale, display vendors do not use FMMs for every single layer, instead, FMMs are only used for absolute necessary layers such as emission layers and optical distance adjustment layers. For the layers not applying FMMs, common metal masks (CMMs) are used. CMM opening covers nearly the entire display area and it does not need precision alignment. In other words, conventional RGB directly patterned OLED displays have many common shared layers among R, G and B sub-pixels. eLEAP, on the other hand, photolithography patterning process etches out all the evaporated materials in between R, G and B sub-pixels so that eLEAP does not have common layers in its OLED device. Fig. 2 shows the concept of structural difference between conventional FMM OLED displays and eLEAP. eLEAP can be used with both single-stack OLED device and tandem-stack OLED device configurations. Since the cathode is also separated, eLEAP can be applied to product designs that require a certain degree of transmittance in display, such as the under-display-camera and the ambient-light-sensor. eLEAP's technical advantages derived from this structural difference are described below.

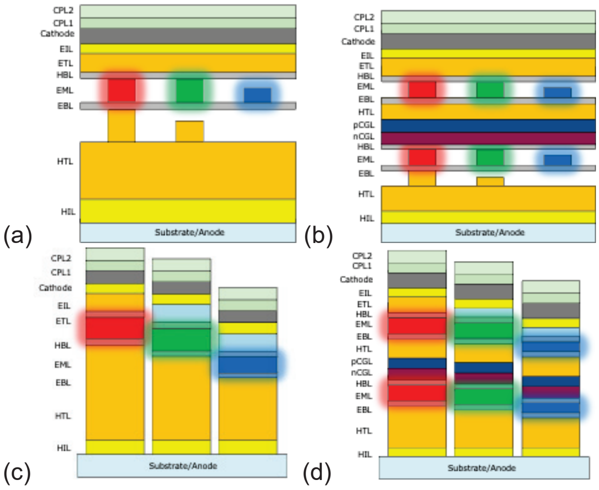

Fig. 2 Examples of (a) single-stack device of FMM OLED (b) tandem-stack device of FMM OLED (c) single-stack device of eLEAP (d) tandem-stack device of eLEAP. All the drawings are simplified and not to scale.

2.2.2 Lateral Leakage

Lateral leakage is known as an OLED display's issue resulting in color and gamma instability due to electrical leakage through common layers. As shown in Fig. 3 (a), conventional FMM OLED display's primary color coordinates shift depending on the luminance levels. This color shift happens more significantly when turn-on voltages are not well aligned between RGB devices and when highly conductive common layers like p-doped HIL and CGL exist. This lateral leakage symptom becomes more significant in low luminance ranges. eLEAP is much more tolerant to this symptom.

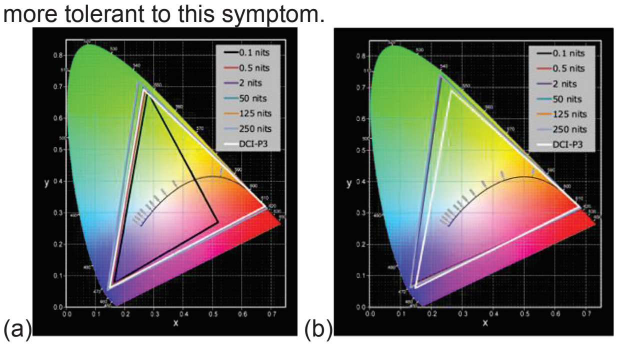

Fig. 3 (a) Conventional FMM OLED display primary colors at different luminance levels (b) eLEAP primary colors at different luminance levels.

2.2.3 p-dopant Concentration

When the lateral leakage is not a concern, p-dopant concentration within HIL is less sensitive to optical performance. To mitigate OLED's driving-voltage increase over continuous display panel operation, adding extra amount of p-dopant may be a good solution.

2.2.4 Growing Dark Spot

When encapsulation structure is damaged for any reason, moisture ingresses from top side of the OLED display and the moisture reaches cathode/EIL electrode. This causes OLED's notorious dark spot issue. To make matters worse the dark spot grows as increased moisture seeps in and propagates. In the case of eLEAP, the dark spot will stay in one sub-pixel, and it will only become a single dark dot.

2.2.5 Material Selection

Conceptually eLEAP is more adaptable to opt for different OLED materials to each RGB layer respectively since no layer is common anymore. In Fig. 2 (a) and (c) are both examples of single-stack OLED devices. In the case of (a) for FMM OLED, common layer materials are chosen to get the best performance for blue device because blue luminescence efficiency is the lowest amongst red, green, and blue. In other words, red and green devices have no choice but to apply the common layer materials originally chosen for the blue device. In the case of (c) eLEAP, each color layer is evaporated separately and sequentially. If there are enough evaporation sources and chambers in the manufacturing line, material selection will not be limited. In that case, red and blue devices do not need to use the same common layer materials any more. This material selection adaptivity will benefit the OLED device design and display manufacturers can fine-tune red, green, and blue device performances respectively to balance efficiency, voltage, lifetime, reliability and so forth.

2.3 Adaptable Shape

Fig. 4 shows the basic structural concept of FMM. Fig. 5 shows the simplified eLEAP manufacturing processes. FMM consists of metal strips, which are also called FMM-stick, Invar stick or mask stick. To stabilize mask aperture positions especially under higher temperatures, the metal strips are welded with tensile stress applied. The width of FMM-stick is usually wider than the active area of the display. In other words, display size is limited by the FMM-stick width. In addition, asymmetric display active area shapes are not typically preferred to uniformly apply tensile force during metal strips welding. eLEAP does not require FMMs, nor requires FMM-sticks, meaning that eLEAP is free from panel size and shape limitation.

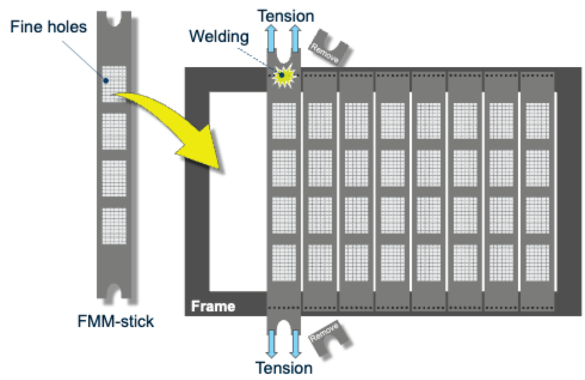

Fig. 4 Fine Metal Mask (FMM) structure.

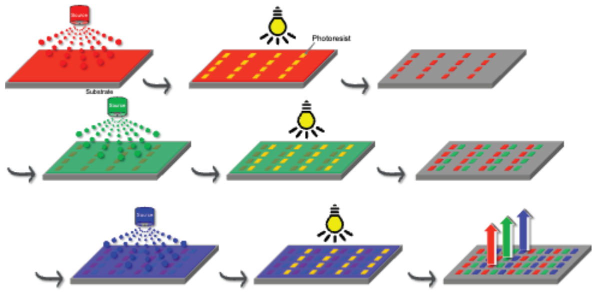

Fig. 5 Simplified Process Flow of eLEAP.

2.4 Environmental Friendliness

When FMMs get evaporated OLED materials on them, accumulated mask thickness will make evaporation shadow and it worsens evaporated film edge profiles. Moreover, repeated FMM-substrate contact creates particles that cause cosmetic and reliability issues. To stabilize manufacturing yield, display vendors need to conduct metal mask cleaning to refresh FMMs very frequently during OLED mass production. In general, FMM cleaning tanks consists of a series of large chemical solvent tanks followed by a series of large rinse tanks, and finally, a drying chamber. eLEAP does not require FMMs, it will eliminate all the FMM cleaning tanks, and a significant saving of CO2 emission can be expected.

3 Discussion

3.1 Display Product Categories

As we have mentioned eLEAP's technical advantages, it is also understood that every display product has different requirements and priorities. In this section, we will review how eLEAP can contribute to each product segment described.

3.1.1 TVs and Signage

In the TV and signage product segment, many display technologies, for instance, QLED, QD-OLED, tandem white OLED, inkjet solution OLED, LCD, tiled LED, projectors are considered mass producible. When eLEAP jumps into this segment, it will be the world's first top-emission RGB directly patterned evaporation OLED display [3-5]. Expectable technology advances are: 1) smoother gamma at low luminance ranges due to its lateral leakage suppression structure, 2) brighter display and/or burn-in tolerance due to top-emission RGB OLED's higher luminescence efficiency, and 3) better reliability due to its sub-pixel independent encapsulation structure.

3.1.2 Automobile

In the automobile product segment, LCD is today's major technology and tandem OLED is expanding its presence in the market [6]. When eLEAP applies to the automobile segment, expectable technology advances are1) adaptable shape especially aiming for pillar-to-pillar slimline OLED display due to FMM free process, and 2) burn-in tolerance due to its tandem friendly process and larger aperture design capability. In automobile usage, good burn-in tolerance, or long lifetime OLED display, is especially important given that its storage and operation conditions may be extremely harsh. Moreover, existing tandem OLED manufacturing requires many metal masks leading to significant carbon dioxide emissions. eLEAP is expected to improve environmental aspects.

3.1.3 Tablet PC and Laptop PC

In the tablet PC and laptop PC product segment, LCD is the major technology being used and is continuously evolving. At the same time, development of evaporation RGB OLED displays for this segment has remarkable momentum and the number of IT products with OLED display is rapidly growing. In order to mass produce IT-size RGB OLED displays with a reasonable cost, larger generation mother glass processes such as generation 8 and larger are desired. When eLEAP jumps into this segment, expectable technology advances will have a smoother transition from existing generation 6 processes to upcoming generation 8 processes and better utilization of panel per mother glass due to FMM free design, better burn-in tolerance due to larger aperture ration, and a slightly slimmer border design. Regarding border dimension; when common metal masks are used in OLED evaporation, TFT glass needs to have a common metal mask mis-alignment margin on border areas. The reasons for having the misalignment margin are to secure cathode contact at the border area and to make the encapsulation design robust. Eliminating the use of common metal masks from the manufacturing process will result in getting rid of the mis-alignment margin so that borders can be consequently slimmer.

3.1.4 Smartphones and Smartwatches

In the smartphone and smartwatch product segment, many cutting-edge display technologies are applied to the products. Major technologies are LCD for the volume zone and RGB OLED for the premium zone. Micro LED is in an intensive development phase towards mass production. When eLEAP comes to this segment, it will provide a better outdoor visibility by giving an option to use displays brighter due to its long lifetime or burn-in tolerance. Also, considering this segment's fast product development cycle, eLEAP's FMM free process can enable quicker design changes and shorten design feedback loops because FMM fabrication lead time usually takes many months especially for new designs.

3.1.5 VR

In the VR product segment, Si backplane substrate displays such as LCoS, OLEDoS and micro-LEDs are used for super high ppi products [7-8]. However, more consumer-intended products use displays with glass backplane substrates such as LCD and OLED. Each technology has different challenges. In the case of Si substrate, due to stepper's exposure shot field angle limitation, the maximum display size is about 1.4" diagonal. When larger size displays are required, fancy techniques like stitching are necessary but it is not mature enough in this extremely high ppi product category. Another challenge is cost, Si wafer is smaller than glass substrate and it is difficult to compete with glass displays when it comes to cost. In the case of glass substrate, the major challenge in VR LCD is contrast ratio, and the major challenge in VR OLED is ppi. Lower ppi is especially critical in VR usage because it causes the "screen door effect" that drastically degrades the sense of immersion for the user. When glass substrate eLEAP comes into VR segment, it can bring higher contrast, as well as higher ppi than conventional glass OLED with a reasonable cost range. In terms of ppi, OLED evaporation will no longer be the limiting process, but TFT becomes the next challenge.

3.2 Technology Maturity

eLEAP has been developed by JDI. Fig. 6 shows the appearance of 14.0-inch rectangular eLEAP prototype samples. In the past, JDI reported 1.4-inch circular design eLEAP and validated the technology concepts. Now with the 14.0-inch eLEAP, its technology maturity and adjustability have been further proven. eLEAP is now considered a mass producible technology, and the first ever eLEAP mass production equipment is now installed in a JDI fabrication line.

Fig. 6 Pictures of 14-inch eLEAP prototypes.

4 Conclusions

As stated in this paper, eLEAP can deliver exceptional value to OLED display products. Not only does eLEAP enhance display performance and user experiences but it is also significantly eco-friendlier than conventional FMM OLED displays. eLEAP samples are available for demo and evaluations, JDI welcomes partnership and commercial use discussions.

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