Light- and space-adaptable display

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ABSTRACT
Presented is a flexible dual-mode display operable in reflective and emissive mode according to ambient light for optimal visibility on a nonplanar surface. Flexible-backplane-embedding organic light-emitting diodes (OLEDs), thin-film transistors (TFTs), and control electrodes for liquid crystal (LC) shutter are realized by the laser lift-off (LLO) method and the newly developed polyimide (PI) delamination technique. A novel color-filterless LC shutter with color dyes is merged with this flexible backplane for operation in reflective mode. This work opens up a promising approach to building displays that are adaptive to the surrounding environment for better usability.

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1. Introduction: concept of light- and space-adaptable (LASA) display

Most people have personally proven that typical displays such as the organic light-emitting diode (OLED) display or liquid crystal display (LCD) on handheld devices like smartphones can be seen barely with bright sunlight. Moreover, batteries run out faster in such cases to raise the brightness. Reflective-type displays like electronic papers will provide much better visibility and longer battery time under this condition [1–3]. It is also known that papers are useless in the dark, and thus, the development of a display that is operable in both the emissive and reflective modes is one of the main goals of the authors.

Meanwhile, the demand for flexible and stretchable device technologies for various applications is growing rapidly, from simple curved televisions to wearable devices [4–6]. It is obvious that such bendable or shape-deformable features will provide ultimate usability to displays, which remain flat and rigid to this day.

In this context, the light- and space-adaptable (LASA) display, which can switch modes among the emissive, reflective, or hybrid modes according to ambient light, and can fit into nonplanar surfaces like the wrist, is proposed. The proposed display is shown in Figure 1.

2. Designing the LASA display

The structure of the LASA display, for which a patent was first filed and granted in the U.S. in 2012 (patent no.: US 9379350 B2), is shown in Figure 2. It is a simple vertical integration of a light shutter and an OLED, and has a common thin-film transistor (TFT) array for the simultaneous active-matrix (AM) driving of both parts. The actual fabrication of the LASA display, however, was quite difficult at its early stage. Thus, a concept of the LASA display could be demonstrated only by making and attaching to each other two separate reflective liquid crystal (LC) and OLED panels, each driven by a TFT array at IMID 2015 [7,8].

Recently, Semiconductor Energy Laboratory Co., Ltd. (SEL) showed a hybrid display fabricated through almost the same vertical integration procedure as was invented by these authors in 2012 [9]. Their hybrid display, however, is a flat-panel type on a rigid glass and thus cannot perform the space-adaptable function. Moreover, they used additional optical components like a polarizer and a color filter for the reflective LC part. This will reduce the luminance of the OLED passing through the optical parts. It will also be a burden to transfer the prototype into flexible or stretchable platforms as this would require increasing the number of stacked layers that should be deformed according to the users’ intention.

Reported herein is an actual prototype of the LASA display. The flexible backplane embeds OLED, TFTs and control electrodes for the LC shutter. It is flexible for the space-adaptable feature. The novel LC shutter presented herein does not need any optical component, such
1. Concept art for the proposed LASA display, which shows adaptiveness to the surrounding environment.

2. Cross-sectional view of the LASA display with an indication of emissive and reflective operation.

Figure 1.

Figure 2.

3. Process flow of the LASA display

The entire fabrication process of the LASA display was designed considering process compatibility among all the components. The LC shutter part is fabricated alone because it is not compatible with the vacuum process for building the TFT and OLED parts. The process temperature for a highly reliable oxide TFT readily exceeds the temperature limit for the organic materials in OLED; thus, the buried electrodes for the LC shutter and TFTs are fabricated first, and OLEDs are formed on them.

The buried electrodes are exposed through the laser lift-off (LLO) technique and the subsequent delamination of the PI film. Finally, the LC shutter is attached to the flexible backplane. The schematic diagrams of the process flow are shown in Figure 3.

3.1. OLED-embedded flexible backplane

3.1.1. Backplane process

The fabrication of the flexible backplane starts with forming a PI film on a carrier glass. SiO$_2$ and SiN$_x$ thin films are sequentially deposited via plasma-enhanced chemical vapor deposition (PECVD). The adhesion strength between the PI film and the SiO$_2$ layer is adjustable by controlling the SiO$_2$ deposition condition. A buried electrode for LC shutter operation is formed on the SiN$_x$ film. Oxide TFT arrays are formed after the deposition of the interlayer dielectric on the buried electrode. Another dielectric layer is formed to separate the OLED part and the TFT arrays. Next, an ITO anode and a pixel-defining bank for OLED are made. Organic materials consisting of OLEDs are sequentially evaporated as follows: 1,4,5,8,9,11-hexaazatriphenylene-hexacarbonitrile (HAT-CN, 10 nm)/N,N’-Di(1-naphthyl)-N,N’-diphenyl-(1,1’-biphenyl)-4,4’-diamine (NPB, 40 nm)/HAT-CN (10 nm)/NPB (40 nm)/HAT-CN (10 nm)/NPB (40 nm)/4,4’,4”-tris(N-carbazolyl)-triphenylamine (TcTa, 10 nm)/PGH02 doped with yellowish-green phosphorescent dopant (8%, 20 nm)/ETM (60 nm)/LiF (1 nm)/Al (100 nm).

Then the OLED is passivated by atomic-layer-deposited Al$_2$O$_3$. Finally, the entire substrate is covered with a PET film using ultraviolet (UV)-curable adhesive.

3.1.2. LLO and PI delamination techniques

The LLO method was used to separate the PI film from the carrier glass without any damage to the OLED and TFT array. After the LLO process, the whole backplane is transferred to the covering PET film and is thus flexible. The remaining PI film has to be removed, however, to expose the buried electrode for the LC shutter. Plasma removal of PI was tested, but residues on and unintended heating of the devices occurred. To address these problems, a SiO$_2$ layer was deposited on PI, as the separation layer. With a properly adjusted SiO$_2$ layer, PI is easily delaminated with very little force. Figure 4 shows the flexible backplane fabricated through the aforementioned procedure.

3.2. LC shutter with a thermal-induced LC composite (TLCC) with color-dye-dispersed polymer

A nematic liquid crystal (NLC)-polymer composite display with specific colors (red, green, and blue) (TLCCD), which can be fabricated through polymerization-induced phase separation in a reactive NLC-polymer mixture, was developed. The thermal-curable NLC-polymer blends consisted of NLC, color dyes, reactants, and a thermal initiator [10,11]. The detailed characteristics of TLCCD will be published separately soon.

3.2.1. Decapping process in LC shutter fabrication for integrating with OLED

Developed next was a novel lamination method for transferring TLCCD to various electronic devices (display,
Figure 3. Schematic diagrams of the process flow for the LASA display depicting the separate fabrication and subsequent merging of the flexible backplane and light shutter.

Figure 4. (a) Flexible-backplane-embedding control electrode for the LC shutter and OLED; (b) Delamination of the PI film; (c) Example of failed PI delamination.

solar cells, smart window, and lighting) regardless of the limitations in the process conditions, such as the temperature, pressure, and cell gap control. To achieve the NLC-polymer composite display, exposure to intense light or to a high temperature is required for a short time to induce fluid-gel phase separation. Therefore, the separate fabrication of TLCCD and such transfer technique are vital to merging the TLCC shutter with the flexible backplane.
3.3. Combining the OLED panel and the LC shutter: prototype of the LASA display

The decapped TLCCD is laminated onto the supporting PET substrate with OLED and TFT arrays. This assembled OLED-TLCCD device is sealed by means of the UV curing method. The obtained TLCCD showed similar electro-optical performances before and after the decapping process. Figure 6 shows the successful dual-mode operation of the segmented-type LASA display.

4. Conclusion

The concept of the light- and space-adaptable (LASA) display, which is adaptive to the surrounding conditions for optimal usability, is introduced. To realize the LASA display, novel technologies were developed, including the PI delamination method to expose the buried electrode, and TLCCD and its decapping for reassembly. It is expected that these technologies can be adopted for the fabrication of multi-functional devices beyond the display.

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Disclosure statement

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