Repeatedly foldable AMOLED display

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Abstract — In this study, a 5.9-inch foldable active-matrix organic light emitting diode (AMOLED) display was developed. A folding test was performed repeatedly. The display survived the folding test (100,000 folds) with a curvature radius of 2 mm. To protect an organic light emitting diode (OLED) against moisture, inorganic passivation layers are provided on the upper and lower sides of the flexible display. Using our transfer technology, high density passivation layers can be obtained. The measured water vapor transmission rate of the layer is 7×10^{-6} g/m^2·day or less, which improves OLED reliability. With these techniques, we have developed a book-type display, which is repeatedly foldable like a book, and a tri-fold display including a display area, which is foldable in three.

Keywords — *OLED, flexible, foldable, oxide semiconductor FET, White tandem, top emission, repeatable folding, WVTR.*

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1 Introduction

Widespread use of small to medium mobile devices, such as smartphones and tablet PCs, has increased rapidly in recent years owing to their portability and convenience. Displays used for such mobile devices must meet certain specifications such as high-resolution, low power consumption, light weight, thinness, durability, and a variety of designs. The physical flexibility of displays is important, particularly in terms of portability and design. Flexible AMOLED displays have attracted significant attention.[1–3] We have previously reported extremely high-resolution flexible AMOLED displays employing a top-emission or bottom-emission white OLED and a color filter.[4–8]

A flexible AMOLED display may be applied to devices that require fixed degrees of bending, for example, static curved or circular forms. Such AMOLED displays may also be applied to devices that require dynamic folding. A dynamically foldable display requires a small curvature radius, which makes it difficult to realize.

There are several key points to be solved with flexible OLED displays, such as protection from moisture in air and prevention of breakage by bending. Generally, a flexible OLED display includes a plastic substrate rather than a glass substrate. Plastic transmits moisture; therefore, passivation films are required on and under an OLED to prevent the OLED from reacting with moisture and degrading. An OLED requires a passivation film with a water vapor transmission rate (WVTR) that is less than 1×10^{-5} g/m^2·day. An inorganic film, such as silicon oxide,

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silicon nitride, or aluminum oxide, is generally used for the passivation film. To reduce WVTR sufficiently, an inorganic film must be sufficiently thick. The plastic substrate and the OLED cannot withstand a high temperature. Therefore, an inorganic film must be formed at a low temperature. Under low-temperature conditions, the inorganic film does not become high density. Thus, the inorganic film needs to be formed thick in order to reduce permeation of moisture. However, when a thick inorganic film is used, productivity is reduced, and breakage occurs easily by bending.

We have solved these problems by fabricating a flexible AMOLED display using a transfer technology that employs inorganic separation layers. The transfer technology process involves a field-effect transistor (FET) array formed on a glass substrate that is separated from an inorganic separation layer by physical force and is then attached to a plastic substrate.

Field-effect transistors formed directly on a plastic substrate must be fabricated at a temperature lower than the heatproof temperature of the substrate. For example, in a method in which polyimide (PI) is applied to a glass substrate, the highest temperature may be approximately 300 °C. In the case of using a laser to crystallize a Si film on the PI film, the laser irradiation causes great damage to the PI film. However, because of the high heat resistance of the inorganic separation layer, our transfer technology enables the formation of FETs at the same temperature at which they are formed on a glass substrate. As a result, FETs with high performance and high reliability can be obtained easily.

We employed a *c*-axis-aligned-crystal oxide semiconductor (CAAC-OS), also called *c*-axis-aligned-nano-crystal oxide semiconductor (CANC-OS); we called "CAAC-OS" hereafter to put them together, for an FET of the display in this paper. As has been reported previously, it has been known that OS films can take the various structures that differ from amorphous or single-crystal structures.[9,10] OS thin films can have a nano-crystal structure, an aggregation of nanoscale microcrystals, and a CAAC structure we developed, which has a *c*-axis aligned perpendicular to the film surface. Figure 1

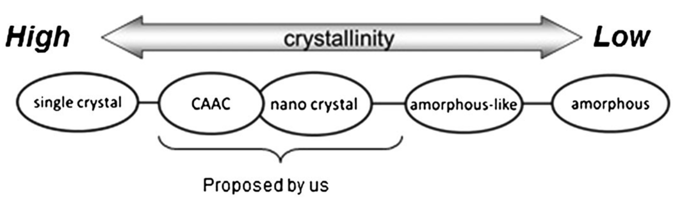

FIGURE 1 — Relation between single crystal, CAAC, nc, and amorphous OS.

TABLE 1 — Specifications of a 5.9-inch display panel.

	Specifications
Screen diagonal	5.9 inch
Driving method	Active matrix
Resolution	720 × RGB × 1280
Pixel pitch	0.102 × 0.102 mm
Pixel density	249 ppi
Aperture ratio	45.2%
Pixel arrangement	RGB stripe
Pixel circuit	5Tr+1C/cell
Source driver	Chip on film
Scan driver	Integrated

FIGURE 2 — Photographs of the prototype book-type display.

shows crystallinity of the CAAC-OS. The CAAC-OS has lower crystallinity than a single-crystal OS but has higher crystallinity than an amorphous OS and an amorphous-like OS.

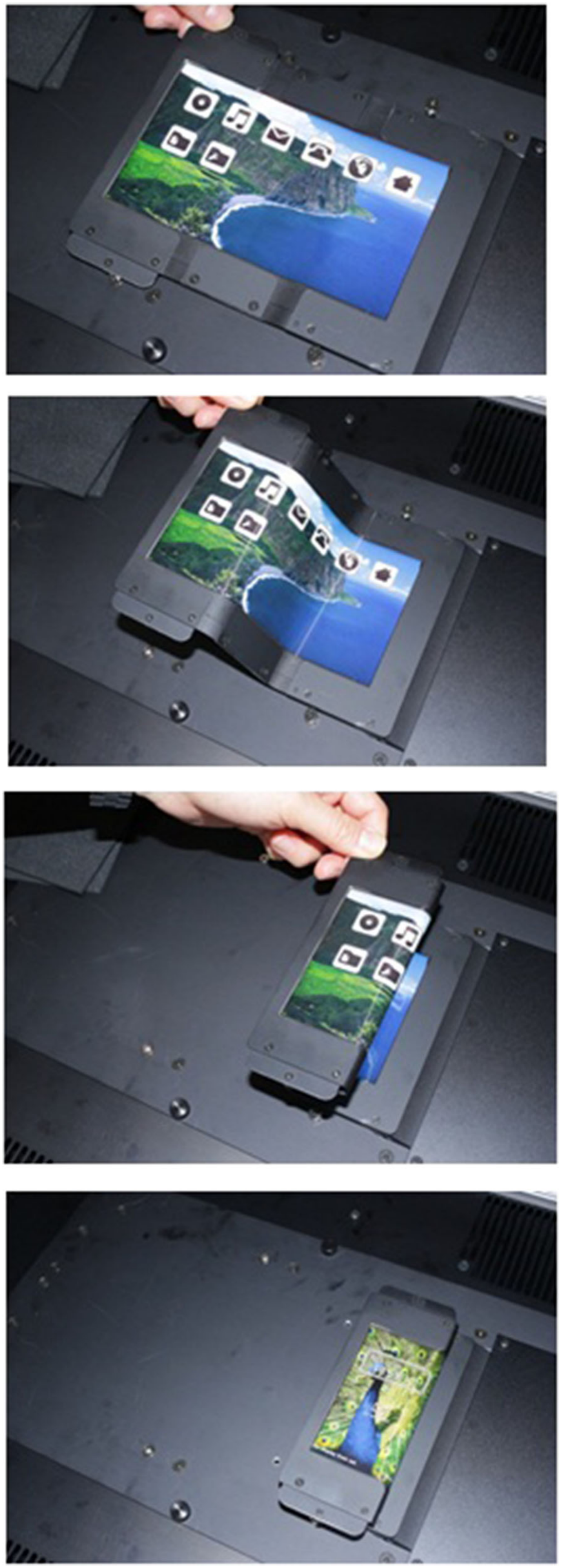

FIGURE 3 — Photographs of the prototype tri-fold display.

Indium Gallium Zinc Oxide (IGZO) can be given as one of the OS's.[11–13] The formation of a CAAC-IGZO thin film on a glass substrate requires annealing at less than 500 °C. We succeeded in forming a channel-etched OS-FET that uses CAAC-IGZO for an active layer and has improved characteristics and improved reliability by lowering the defect levels.[14]

Low-temperature polysilicon (LTPS) has been used for backplanes of small-sized and medium-sized displays. However, LTPS has some problems. For example, displaying a still image consumes a large amount of power due to a high off-state current; manufacturing requires a large number of steps, which increase costs, and special manufacturing equipment such as laser irradiation and ion doping apparatus is required. Although we have developed LTPS,[15–18] we have also developed a CAAC-OS with fewer drawbacks. A CAAC-OS has some advantages: A still image is displayed with low power consumption due to a low off-state current; and a resolution as high as that of LTPS can be obtained. In addition, laser irradiation and ion doping are not required for a CAAC-OS.

In this paper, we newly fabricated a 5.9-inch foldable book-type AMOLED display and a 5.9-inch tri-fold type AMOLED

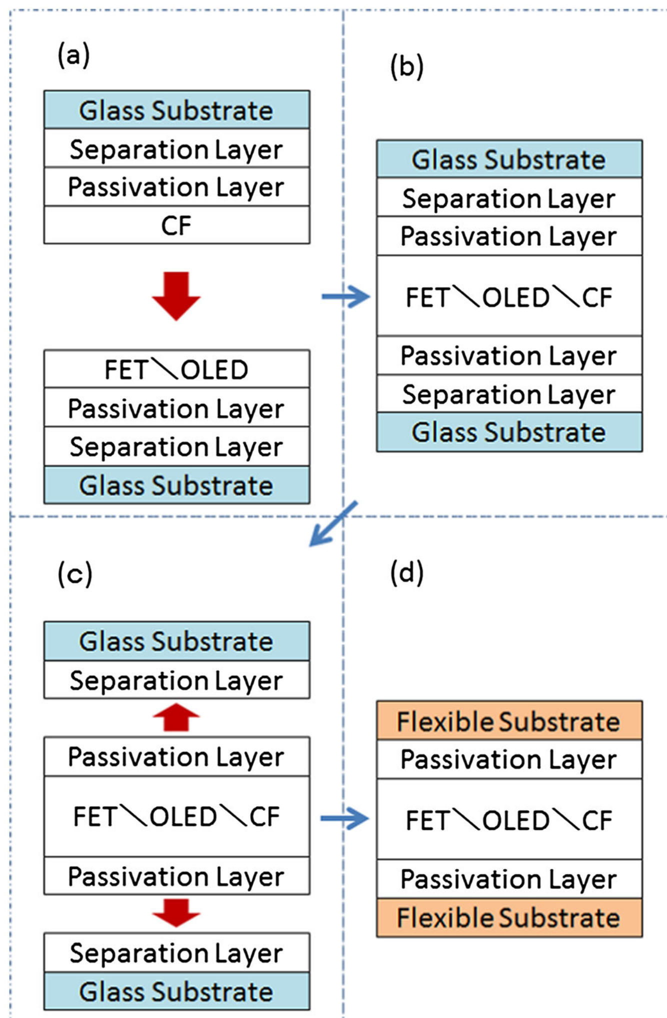

FIGURE 4 — Method for fabricating a flexible AMOLED using transfer technology.

display. Moreover, we report the measurement results of WVTR of a passivation layer and the results of a repeated folding test.

2 Specifications and characteristics of prototype displays

With our original transfer techniques, we prototyped a 5.9-inch foldable book-type AMOLED display and a 5.9-inch tri-fold display each of which may be applied to a smartphone or a tablet. Table 1 shows the specifications of the displays. The pixel density of each of the 5.9-inch panels was 249 ppi. A scan driver was incorporated into a bezel of each of the panels, and a source driver was attached externally by Chip On Film.

Photographs of the 5.9-inch prototype displays are presented in Figs 2 and 3. As can be seen, these displays are sufficiently strong against folding. These displays were driven without problems when they were bent while displaying an image. The curvature radii of the folded portions were 5 and 4 mm in the foldable book-type display and the tri-fold display, respectively. In the tri-fold display, the panel displays different images in the unfolded and folded states, which are detected by a sensor. Thus, driving of an out-of-sight display area in the folded state can be stopped, leading to power saving.

TABLE 2 — Number of folding times[a] carried out in the repeated folding test (3.4-inch display).

	Radius of curvature			
	5 mm	3 mm	2 mm	1 mm
Type 1	>100,000	>100,000	>100,000	<4,000
Type 2	>100,000	>100,000	>100,000	<70,000

[a]Number of folding times with no defects occurring and driver operating normally after the test.

3 Flexible active-matrix organic light emitting diode fabrication method

Figure 4 shows a method for fabricating a flexible AMOLED using our transfer technology.

First, a separation layer, a passivation layer, an FET layer, and an organic electroluminescence (EL) layer were formed on a glass substrate. For the separation layer, a film made from tungsten is used. And the passivation layer comprising stacked several layers of inorganic material was formed on the separation layer. Separation did not occur immediately after the formation. However, reaction occurred by performing baking treatment. The reaction changes the state of the interface, and brittleness is exhibited, leading to physical separation with a trigger for separation.

We employed a top-emission white OLED for the organic EL layer. The organic EL component had a two-layer tandem structure consisting of a blue fluorescent material and green and red phosphorescent materials. The FET was an oxide semiconductor FET having a CAAC structure. The CAAC structure is not amorphous; thus, there are few defect levels, and the FET has high reliability. Furthermore, grain boundaries are not clear; thus, in a flexible display having the CAAC structure, cracks are not easily formed. For the pixel electrode, a Ti film (5–10 nm thick) was formed over an Al electrode to prevent increased resistance due to oxidation of the Al surface, and an ITO film was formed over the Ti film. The thickness of the ITO film varied depending on the color of the pixel; thus, the total thickness of the ITO film, the EL layer, and the cathode was appropriately adjusted to produce a microcavity effect.[5] Because this structure cannot provide sufficient color purity, a color filter (CF) was additionally provided on the counter substrate.

A separation layer, a passivation layer, and a color filter were formed over the other glass substrate. Then, as shown in Fig. 4(b), the FET substrate and the color filter substrate were bonded. The cell gap between the FET substrate and the color filter substrate was approximately 5 μm. After bonding, the

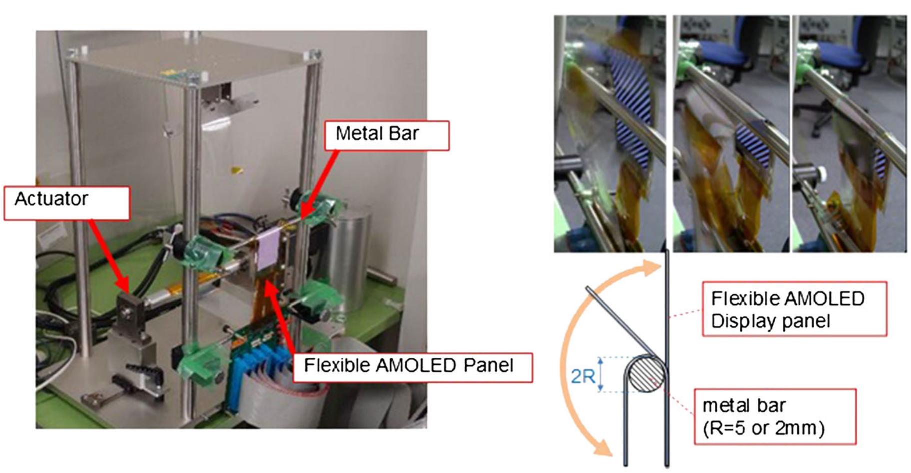

FIGURE 5 — Repeated folding test (Type 1).

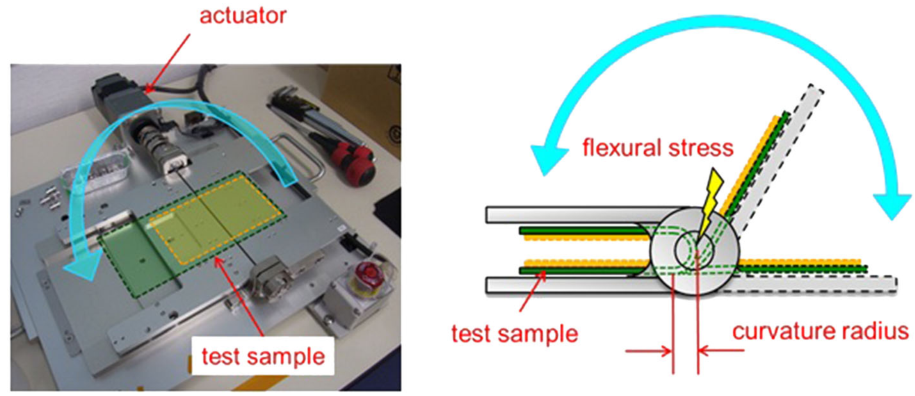

FIGURE 6 — Repeated folding test (Type 2).

upper and lower glass substrates were separated from the passivation layers by physical force as shown in Fig. 4(c). Then, the flexible substrates were bonded as shown in Fig. 4(d).

We used 20-μm-thick plastic films with a low thermal expansion coefficient for the flexible substrates.

4 Repeated folding test

The 3.4-inch flexible AMOLED display fabricated by the method described in Section 2 was subjected to a repeated folding test using a repeated folding test machine. The specifications of the display are the same as those in Table 2.

Figure 5 is a photograph of the repeated folding test machine and images how the repeated folding test was performed (Type 1). And Fig. 6 shows another repeated folding test (Type 2). The portion to be folded was placed in the middle of the panel and included part of a display area and a scan driver area. Folding was repeated 100,000 times. The folding curvature radius was set by a metal bar. For example, when the diameter of the metal bar was 10 mm, the curvature radius was 5 mm. The panel was folded such that the display surface (color filter side) was on the inside (facing inward).

Table 2 shows the results of the repeated folding test. For both curvature radii of 5 and 2 mm, no defects occurred in the display area, and the driver operated normally after 100,000 folds.

5 Measurement of water vapor transmission rate

To evaluate the passivation layer, we formed a sample and measured the WVTR. Figure 7 shows the structure of the sample. In the sample, the FET, the OLED, and the color filter in the structure described in Fig. 4 were not included. The measurement was performed using "HiBarSens" (Fraunhofer IWS, Dresden, Germany and Sempa Systems GmbH).

Figure 8 shows the results of the WVTR measurement. The WVTR under water vapor conditions of 38 °C and 90% RH after sufficient time had elapsed was estimated to be less than or equal to 7×10^{-6} g/m^2·day.

6 High-temperature and high-humidity test of flexible display panel

A high-temperature and high-humidity test was performed on the flexible display fabricated by the method described in Section 3.

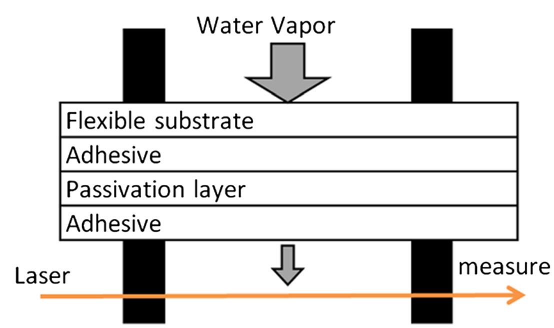

FIGURE 7 — Structure of sample for measurement of WVTR.

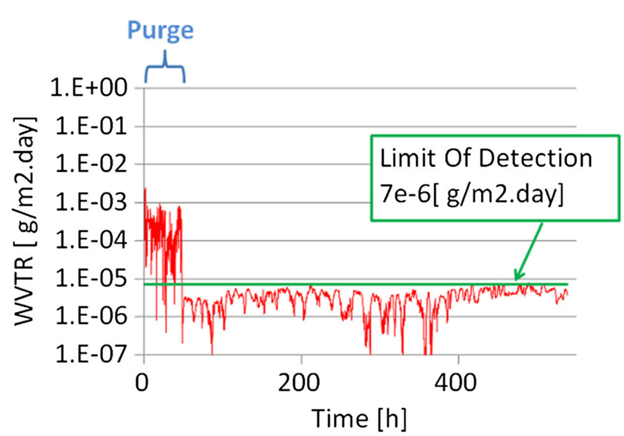

FIGURE 8 — WVTR measurement results (38 °C/90% RH).

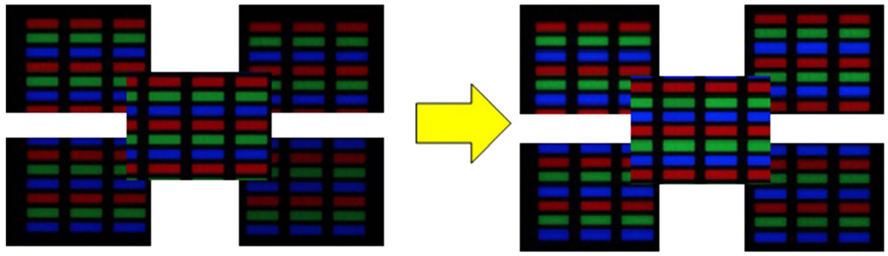

FIGURE 9 — High-temperature and high-humidity storage test (micrographs of the central area and four corners of the flexible display.

This display was stored in an environment of 90% humidity and at 65 °C for a long time. Figure 9 shows micrographs of pixels in the central area of the display observed before and after the test. Generation of a dark spot and pixel shrinkage was not observed after 500 h. Thus, the passivation film has high quality enough to withstand duration of 500 h.

7 Conclusion

A flexible AMOLED display including a CAAC-OS FET (or CANC-OS FET) and a white tandem OLED was fabricated using inorganic separation layers. The display was subjected to a folding test (100,000 folds) with a curvature radius of 2 mm and performed without problems. The WVTR of the passivation layer was determined to be less than or equal to 7×10^{-6} g/m^2·day, which, in terms of performance, is highly favorable. We have successfully fabricated a 5.9-inch foldable book-type AMOLED display and a 5.9-inch tri-fold AMOLED display for a smartphone, which has the aforementioned structure. The very small bend radius that these displays are able to tolerate, together with the tolerance of a large number of folding and dynamic bending cycles will, for the first time, enable new reconfigurable devices to be realized.[19]

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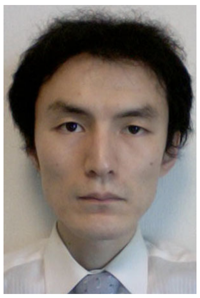

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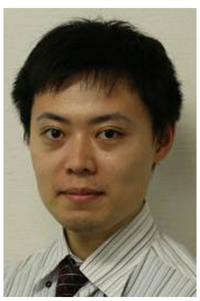

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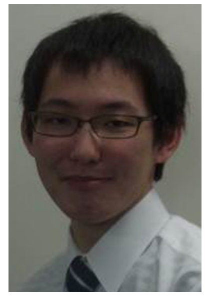

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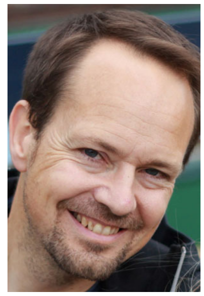

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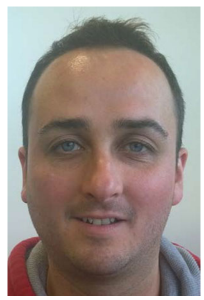

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