Effect of Contaminant Particles on Folding of Encapsulating Organic-Inorganic Multilayer for Foldable OLEDs

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ABSTRACT

The effect of contaminant particles on the folding of encapsulating organic-inorganic multilayer was investigat ed. The stability of the organic-inorganic multilayer thin fil ms was evaluated when they were folded inward or outw ard in 1 mm radius according to the size of the contamina nt particles and the thickness of the multilayer thin films. It was confirmed that the organic- inorganic multilayer films deposited by the atomic layer deposition and plasma-enh anced chemical vapor deposition methods completely cov ers the contaminant particles regardless of the size of the particles. However, due to the angle of curvature in the res ulting encapsulation structure caused by the presence of t he contaminant particles, higher stress is generated arou nd the particles and the cracking due to folding is more e asily occurred. In this study, we proposed the stability crit eria for the thickness of encapsulation layer upon folding even in the presence of contaminant particles

1 INTRODUCTION

We have secured the stability of OLED devices by enc apsulation with thin film of organic / inorganic composite l ayer by vitex method. However, as the research of foldabl e display or rollable display becomes more active, the me chanical properties of encapsulation layer will be seriousl y deteriorated by contaminant particles, and it is time to id entify it. The objective of this study is to investigate the pa rticle coverage of the encapsulation thin film when the co ntaminant particles are present on the surface of the OLE D devices and to evaluate the effect of the covered particl es on folding of the encapsulation thin film. This study is v ery important in the implementation of foldable OLEDs an d ultimately aims to provide a criteria for stable thickness of thin film encapsulation for folding.

2 EXPERIMENT

This section describes the details about the text content of the manuscript. An Al_2O_3 thin film grown by atomic layer deposition (ALD) was used as the thin film encapsulation l ayer for this study. The organic layer used in this study ca used plasma phenomenon by using n - hexane. The plas ma polymer layer fragments the organic material from the polymerization by-products of the radical. First, a 1-μm-thick poly (methyl methacrylate) (PMMA) layer was sp in-coated onto a 50-μm-thick polyimide (PI) substrate for

surface planarization. Since a poly (ethylene

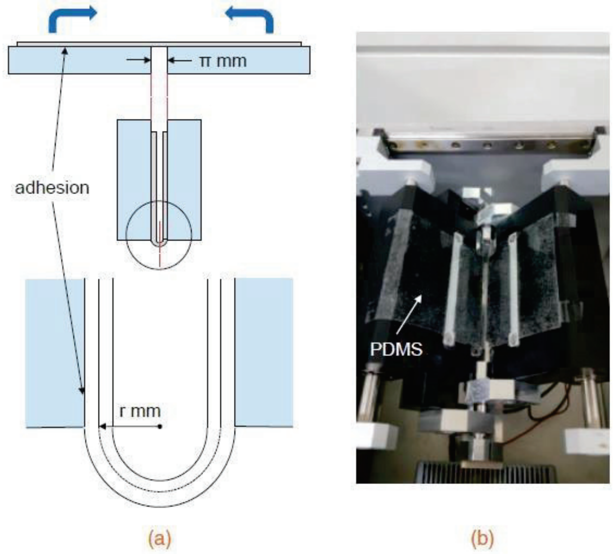

Fig. 1. Folding condition
(a) Schematic diagram of 1 mm diameter folding.
(b) Photographic image of folding apparatus.
Two folding plates are spaced π mm apart and designed to have a spacing of 2 mm at the folding. The sample is tightly attached to the PDMS surface on the folding plate during the folding.

terephthalate) substrate of the same thickness is damag ed by repetitive folding, we utilized a PI substrate causin g no damage under the same condition owing to the rel atively low Young's modulus. Polystyrene was used as contaminated particles, and diluted 1: 1000 with IPA. An d spin coating was carried out at 4000 RPM conditions f or application. Al_2O_3 and plasma polymer layers were d eposited on the contaminated substrate by ALD and pla sma-enhanced chemical vapor deposition, respectively. For the deposition of the Al_2O_3 layer, TMA and ozone we re used. Each precursor was injected into a deposition c hamber maintained at a pressure of 3×10^{-2} Torr for 2 s. After the injection of each precursor, the chamber was purged for 10 s using argon (Ar) gas. The substrate temperature was maintained at 90 °C and the Al_2O_3 growth rate per cycle was 1.2 Å. The plasma poly mer layer was deposited in Ar plasma using n- hexane a nd the deposition rate was 20 nm/min. The water vapor transmission rate (WVTR) of the fabricated encapsulati on layers was measured by the Ca test. The measured WVTRs of contaminated 10 dyad multilayer (1 dyad: 5-nmthick Al_2O_3 layer and 20-nm-thick organic layer) was 7 × 10^{-4} gm^{-2} day^{-1}, respectively. Here, the Al_2O_3 layer grown by ALD has excellent moisture resistance, whereas the plasma polymer has poor moisture resistance and thus does not significantly affect the WVTR. Therefore, the thickness of the Al_2O_3 layer was fixed at 50 nm, and the folding stabilities of the inorganic single layer and organic-inorganic multilayer with the same total thickness of the Al_2O_3 layer were evaluated. However, in the case of the organic-inorganic multilayer barrier, a lower WVTR is usually obtained because the path of the moisture penetrating through the defects becomes tortuous. Nevertheless, it was confirmed by the WVTR (8 × 10^{-4} gm $^{-2}$ day^{-1}) that the barrier properties were maintained when 1R folding was performed after contaminant particles were applied. In addition, the side state was checked by using a Focused Ion Beam (FIB) to check whether the barrier was broken during 1R folding in the presence of contaminant particles.

3 RESULTS

In this paper, we can recognize thin film encapsulation for stable foldable OLED display is advantageous as the thickness of encapsulation layer is thinner. If contaminant particles are present in the foldable OLED display, when the encapsulation layer is thick, it can cover the particles sufficiently and be stable even when folded. On the other hand, if the thickness of the encapsulation layer is very thin, the contaminant particles may not be covered enough, encapsulation layer crack due to folding. As the structure of the organic-inorganic multilayer encapsulation layer, a structure in which 5nm Al_2O_3 inorganic layer and 60nm plasma polymer layer was alternately stacked 10 dyads was always stable to 1R folding.

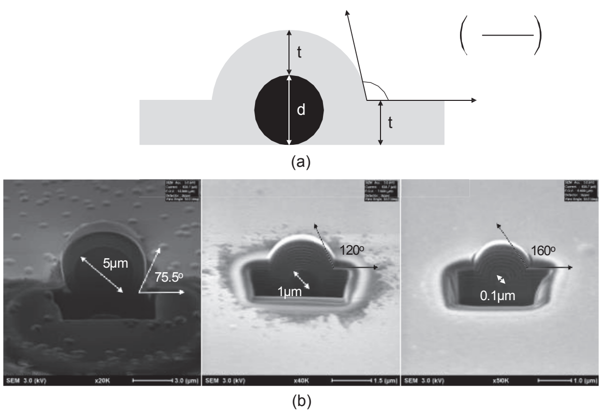

Fig. 2. (a) Schematic diagram representing 100% step coverage of an encapsulating thin film (thickness t) onto a particle (diameter d); (b) cross-sectional SEM images . of particles encapsulated with organic-inorganic multilayer thin film.

If the organic-inorganic multilayer encapsulation layer with a total thickness of (t) completely covers 100% of spherical contaminant particles with diameter (d), it must have a covering angle as shown in Fig 2 (a). In fact, the organic-inorganic multilayer encapsulation layer was deposited on spherical particles having a diameter of 5,1 and 0.1 μm, and the coating angles were found to be in close agreement with the expected coating angles. The larger the size of the contaminated particles, the lower the coating angle, and in the case of in-folding folding toward the top of the particles, cracking is most likely from the periphery of the polluted particle with the lowest coating angle. Therefore, the occurrence of cracking by folding is expected to depend on the size (d) of the contaminant particles and the thickness (t) of the encapsulation film. The effect of contaminant particles on the crack formation of the encapsulation film was investigated when the contaminant particles were present in the fold.

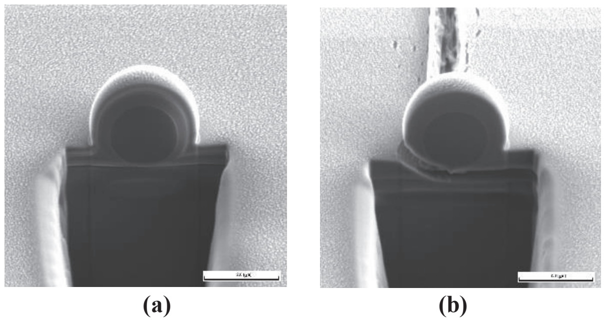

Fig. 3. (a) Cross-sectional SEM image showing around a contaminant particle before 1R in-folding. (b) Cross-sectional SEM image showing a crack originated from a perimeter position around a contaminant particle after 1R in-folding.

Fig. 3 is a SEM photograph of cracks generated after 1R repeated folding after depositing spherical particles having a diameter of 2 μm by depositing 5 nm Al_2O_3 inorganic thin film and 60 nm plasma polymer thin film alternately. The total thickness of this organic-inorganic multilayer encapsulation thin film structure is 590 nm. Calculating the cover angle using the equation shown in Figure 2 shows that it is about 75°. The actual measured coating angle was about 82°, and it was confirmed that the crack occurred in the circumference of the polluted particle with the steepest coating angle when 1R in- folding folding occurred at the coating angle.

Fig. 4 is a SEM photograph of cracks generated after 1R repeated folding after depositing spherical particles having a diameter of 2 μm by depositing 8 μm planarization layer by PECVD. After planarization layer, deposited encapsulation a structure in which 5nm Al_2O_3 inorganic layer and 60nm plasma polymer layer was alternately stacked 10 dyads. The total thickness of this organic-inorganic multilayer encapsulation thin film structure is 8590 nm. Calculating the cover angle using the equation shown in Figure 2 shows that it is about 141°. The actual measured coating angle was about 146°. After 1R folding, it can't find crack around contaminant particles.

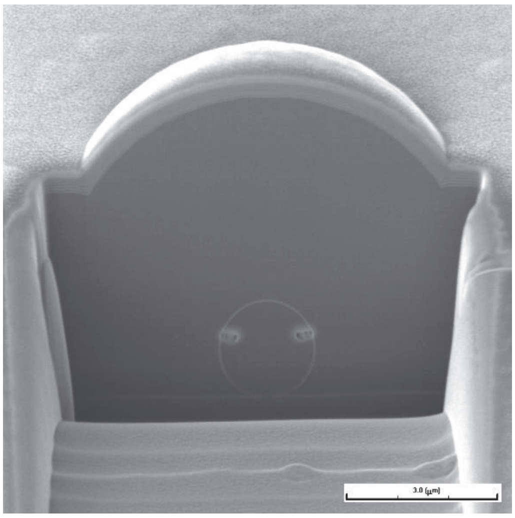

Fig. 4. Cross-sectional SEM image showing a contam inant particle with planarization layer after 1R in-foldi ng

4 DISCUSSION

In fact, there is a possibility that large contaminant part icles are generated in the manufacturing process of OLE D display, and if the large contaminant particles exist on t he surface before the thin film encapsulation process, the surface is flattened before the thin film encapsulation to minimize the occurrence of cracks in the repeated folding process. It is necessary to loosen the surface coating an gle of the thin film to 140^{o} or more by performing the proc edure.

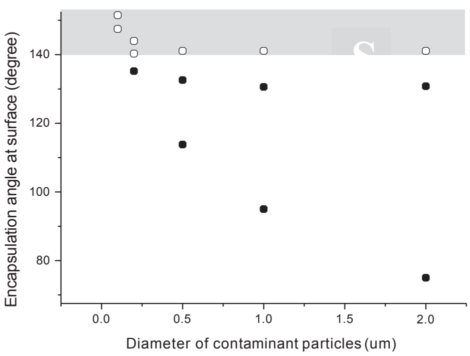

Fig. 5. 1R folding stability of organic-inorganic multila yer encapsulation structure when contaminant particl es exist on the folding surface.

As shown in Fig. 10, when the coating angle was more than 140^{o}, it was found to be stable to 1R in-folding folding.

5 CONCLUSIONS

From the above results, organic-inorganic multilayer encapsulation layer deposited by ALD and PECVD is conf irmed that the coating uniformity of contaminant particles i s about 100%. When contaminant particles are present a nd folding occurs, cracks are generated near the perimet er of the contaminant particle. The occurrence of cracks is closely related to the covering angle, which can occur more often in-folding than out-folding. If the coating angle was looser than about 140^{o}, it was found to be sta ble even for folding in 1R. Even if there are contaminant particles, it is very important to planarization before depo sited thin film encapsulation layer so that the coating an gle is loosened to more than 140^{o} around particles. This research is looking forward to be used not only for the fo ldable OLED display under development but also for the encapsulation layer for rollable or stretchable OLED dis play.

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